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SOLAR GAMMA RAY AND NEUTRON OBSERVATIONS+

by

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Invited paper presented at a Symposium on High Energy Phenomena on the Sun, Goddard Space Flight Center, Greenbelt, Maryland, 28-30 September 1972.

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SOLAR GAMMA RAY AND NEUTRON OBSERVATIONS

ABSTRACT. The present status of knowledge concerning the impulsive and the continuous emission of solar gamma rays and neutrons is reviewed in the light of the recent solar activity in early August 1972. The gamma ray spectrometer on OSO-7 has observed the Sun continuously for most of the activity period except for occultation by the Earth. In association with the 2B flare on 4 August 1972 and the 3B flare on 7 August 1972, the monitor provides evidence for solar gamma ray line emission in the energy range from 300 keV to 10 MeV. A summary of all the results available from preliminary analysis of the data will be given. Significant improvements in future experiments can be made with more sensitive instruments and more extensive time coverage of the Sun.

I. INTRODUCTION

The aim of this discussion is to review the status of the experimental efforts to search for gamma rays and neutrons emitted from the Sun. Most of these efforts concern observations during quiet solar periods and during realtively small flares ≤2B. At the time Dr. Ramaty organized this conference, we would have had to be content in reviewing the many noble efforts which have been carried out to bring into viable existence a new probe for studying solar phenomena. Fortunately though, the significant solar activity of early August 1972 allows us to review this field while both the Sun and some satellite experiments were closely in tune. We therefore will have to consider our remarks in the light of new and interesting observations. Before 1970 the typical limiting flux values for neutrons (≥20 MeV) was $\sim 10^{-2} cm^{-2} sec^{-1}$. These early results essentially all referred to continuous emission of neutrons by the Sun. Since that time satellite and balloon neutron experiments have been greatly improved so the neutron flux limit has been reduced by an order of magnitude to $\sim 10^{-3} cm^{-2} sec^{-1}$ for continuous limits. Limiting fluxes for gamma rays (<10 MeV) have remained at the same level; for example, $5 \times 10^{-3} cm^{-2} sec^{-1}$ for the 2.2 MeV lines. Efforts to detect π° decay gamma rays (>10 MeV) have also continued with no clear success. In addition, the realization that mountain top cosmic ray neutron monitors can potentially detect solar neutrons, coupled with Monte Carlo calculations of solar neutron secondary production in the atmosphere, have allowed continuous search during large events back to 1960. Satellite neutron detectors on OSO-6 and OSO-6 have also extended the time coverage during times of significant solar activity. All of the

mentioned above have continued to give only upper limits for solar neutron and gamma ray fluxes under both active and quiet solar conditions.

A new development has just occurred recently with measurements made by a gamma ray monitor on the OSO-7 satellite. Gamma ray lines have definitely been detected during at least two of the several flares which occurred in the period from 2 August to 11 August 1972. Since the neutron-proton capture gamma ray was one of the lines detected, these observations give comprehensive data on both the neutron and gamma ray fluxes with a single instrument

II. SUMMARY OF WORK TO AUGUST 1972

The experimental investigations to detect solar neutrons and gamma rays, which were reported in the literature by 1970, were reviewed previously by Chupp (1971). Up to that time there was no conclusive evidence for either solar neutron or gamma ray fluxes. On the other hand, there were at least three highly disputed claims of observations of both solar neutrons and gamma rays all in times of modest or low solar activity. None of these "possible" events occurred in coincidence with the optical phase of any flare. Nonetheless, since they are published as positive fluxes, we should keep the reports in mind and the conditions of solar activity under which they were observed. The Tata result of Apparao et al. (1966) was obtained under very quiet solar conditions; that of Daniel et al. (1967) was made several hours before a subflare. This result was seriously questioned by Holt (1967) since no neutron decay protons were seen by the OSO-A satellite, which was in orbit at the time and should have been

them if the neutron flux was 10^{-1} neutrons $cm^{-2}sec^{-1}$ as reported. This criticism has now been countered by Daniel et al. (1971) who have revised their result downward nearly an order of magnitude to 1.5×10^{-2} neutrons $cm^{-2}sec^{-1}$ based on a new measurement of the atmospheric neutron flux which allowed them to convert the measured solar neutron counting rates to an absolute flux. It seems this result will not go away. In the case of gamma rays, Kondo and Nagase (1969) reported an extremely large (800 percent) increase in the gamma ray flux (3-10 MeV) 10 minutes after a 1N flare and associated radio burst. The last positive report of a gamma ray increase was given by Hirasima et al. (1970) who reported a gamma ray line flux coincident with a 1000-MHz radio burst. As satellite experiments in the future continue to search for gamma ray and neutron events, it will be interesting to see if any enhancements are found under similar activity conditions as in the cases just discussed. Then we can decide if indeed these peculiar observations are most probably positive or spurious.

Several significant experiments summarized in Table I have been discussed in the literature since the review mentioned above. Joseph (1970) has reported on the results of measurements at Tata using a new type of high energy detector and a plastic scintillator. The basic neutron-detecting element for the new detector consists of a CsI(Tl) crystal slab of 4 3/8" diameter by 0.5 cm thickness and associated photomultiplier in a 1-cm thick plastic scintillator anticoincidence shield. Fast neutrons, 10 MeV $< E_n$ $<$ 500 MeV, produce nuclear reactions, primarily stars, giving

Table 1

Summary of the recent Solar Neutron and Gamma Ray Observations to August 1972

Reference	Instrument	Radiation and Energy Range	Neutron or Gamma Ray Flux ($cm^{-2}sec^{-1}$)	
			Continuous	Flare Associated
Joseph thesis (1970)	Plastic Scintillator Telescope with antishield	n 15-150 MeV γ 5-30 MeV		2B, 1N 2-26-69 n $<1.2 \times 10^{-2}$ γ $< 10^{-2}$
Cortellessa et al. (1971)	Plastic Scintillator with antishield	n 10-200 MeV	$<5.5 \times 10^{-3}$	1N 6-30-70 Protons $< 6 \times 10^{32}$ above P0=60 MV 30 MeV
Eyles et al. (1972)	Scintillator Recoil Telescope with antishield	(i) n 50-350 MeV γ >80 MeV (ii) Test of Elliot Model	n $<3 \times 10^{-3}$ γ $<4 \times 10^{-4}$	(i) 1B 5-29-69 n $<23\ cm^{-2}$ γ $< 6\ cm^{-2}$ (ii) 2B 3-21-65 n $<4.2 \times 10^{-3}$ Theo. $\sim 5 \times 10^{-2}$ for Class 4
Sood (1972)	Cerenkov pair Telescope with Pb converter	γ >20 MeV		1N 10-17-68 γ $<2.6 \times 10^{-4}$ (10 min rise) $<1.1 \times 10^{-5}$ (active disc)
Lockwood et al. (1972) OGO-6	He^3 proportional counter with antishield	n 1-20 MeV	$<1.8 \times 10^{-3}$	Null Results
Leavitt et al. (1972) OSO-6	Scintillator Recoil Telescope	n >40 MeV	$<4 \times 10^{-4}$	Null Results

rise to proton, alpha particle, or other ion pulses in the slab. Pulse shape discrimination has also been used to separate out neutron-induced star events from gamma ray events which produce energetic electrons in the crystal. The sensitivity (area x efficienty) of this detector for fast neutrons is ~ 0.75 cm^2 above 10 MeV. In addition, the detector is sensitive to gamma rays in the energy range 4→30 MeV, but no estimate is given for the efficiency. The properties of the scintillator block were very similar to those previously discussed by Forrest and Chupp (1969). The basic property of this detector needed in this discussion are the sensitivities for solar neutron and gamma rays, which are 22 cm^2 for neutrons (>10 MeV) and 30 cm^2 for gamma rays (5→30 MeV). These instruments have been flown in 1969 from Hyderabad (λ_{gm}=8°N) during coincidental solar activity. During a 2B (and following 1N) flare on 26 February 1969, the plastic block detector observed no increase; therefore, limiting fluxes for solar neutrons were $\leq 10^{-2}$cm^{-2}sec^{-1} (5-30 MeV). On 19 April 1969 the smaller volume CsI(Tl) star detector was flown during a 1B flare with no enhancement observed. The corresponding upper limit for solar neutrons in this event was 1.5×10^{-2}cm^{-2}sec^{-1} which is essentially the same as for the larger plastic block detector. The reason for this is that even though the sensitivity of star detector is much lower than for the former, its background counting rate is correspondingly much lower. All of these limit estimates apply to the case of an assumed neutron spectrum produced by a solar proton exponential rigidity spectrum with P_o = 60 MV (Lingenfelter and Ramaty 1967).

Cortellessa et al. (1971) have carried out several careful measurements using an anticoincidence shielded plastic scintillator in 1970, which studied both continuous emission possibilities as well as in small flares. The detector was sensitive both to neutrons and gamma rays with the biases for neutrons set at equivalent proton recoil energies of 10 MeV, 20 MeV, and 30 MeV. Self-gating effects due to recoil protons from the surface of the inner detector interacting in the antishield were reduced by surrounding the inner detector with 1 cm of Al. The effective neutron energy range of the detector then was 10 MeV→ 200 MeV, with an efficiency for solar neutrons of ~11 percent based on an assumed solar neutron production spectrum due to a solar proton spectrum with characteristic rigidity P_o = 60 MV. The continuous solar neutron flux limit was 5.5×10^{-3} neutrons $cm^{-2}sec^{-1}$, in the energy range of the detector, for flights in 1970. In addition, failure to detect any neutrons in a flight during a 1N flare on 30 June 1970 gave a limit for accelerated protons at the Sun of $<6 \times 10^{32}$ protons with energies >30 MeV, for P_o = 60 MV. In order for these workers to achieve the improved limits (shown in Figure 1), care had to be taken to keep instrumental instability effects on the counting rate B, to less than 2 $(BT)^{-1/2} \times 100$ for an observing time T. In this case the instability effects were reduced to 0.28 percent.

Eyles et al. (1972) have reported on the results of balloon flights with a recoil telescope designed to test the predictions of Elliot (1969) concerning acceleration of charged particles before the optical flare with consequent release into the solar

atmosphere thus providing the energy source for the optical flare. The apparatus consists of a polyethylene block of thickness 16.5 gm/cm^2 as a converter, followed by a recoil proton telescope, all in an anticoincidence shield comprising the neutron telescope. This unit was followed by a Cerenkov element, 1-cm thick, to eliminate 95 percent of relativistic charged particles. The detector's neutron response was effective over an energy range from 50 MeV to 350 MeV with a maximum efficiency at ~190 MeV of ~1.4 percent, falling steeply on both sides of the maximum. Using the converter area of ~181 cm^2 gives a maximum sensivitity of ~2.5 cm^2. The telescope half angle for neutrons was ~22°. The detector was also sensitive to gamma rays with energies about 20 MeV. At 100 MeV the gamma ray efficiency was 35 percent. This detector was flown in 1969 to give limits both during active periods and quiet periods. The neutron and gamma ray limits for continuous emission are $3 \times 10^{-3} cm^{-2} sec^{-1}$ (50→350 MeV) and $4 \times 10^{-3} cm^{-2} sec^{-1}$ (~20 MeV) respectively. This neutron limit is even lower than that mentioned above by Cortellessa et al. (1971). Even though the sensitivity is an order of magnitude lower for the telescope, the background is much lower. During a 1B flare on 1 November 1969 the limiting neutron and gamma ray fluxes found were $\leq 4 \times 10^{-2} cm^{-2} s^{-1}$ and $\leq 10^{-2} cm^{-2} s^{-1}$ respectively.

There was however an opportunity to test, to some extent, the predictions of Elliot's model (Elliot 1969) four hours before a 2B flare on 21 March 1969. No neutron flux was detected above a limit of 4×10^{-3} neutrons $cm^{-2} sec^{-1}$. Since Elliot's model predicts a flux of ~5×10^{-2} neutrons cm^{-2} sec^{-1} for a Class 4 flare,

the authors do not consider this example as a real test of the preflare acceleration model since even much lower fluxes are expected for smaller optical class flares.

Sood (1972) has also conducted a search for high energy gamma rays from the Sun in order to test the Elliot model (Elliot 1969). His instrument consisted of a pair telescope with a Pb converter. In addition, unidirectional Cerenkov elements were used to detect the relativistic electrons. The instrument was not sensitive to photons with energies <20 MeV but had an overall efficiency for π° gamma rays of ~38 percent and the area solid angle factor was 22 cm^2sr. Several flights were carried out in 1967 and 1968 from Kampala, Uganda, while the Sun was moderately active. For a generally active solar disk, the limiting flux was $\leq 1.1 \times 10^{-4}$ gammas $cm^{-2}sec^{-1}$ (>50 MeV), and for a 1N flare on 19 October 1968, the limiting flux was 2.6×10^{-4} gammas $cm^{-2}sec^{-1}$ assuming a 10-minute burst. One flight took place ~8 hours before a 2B flare on 31 October 1968 but since no 350 MeV protons (π° threshold) were observed in space following this flare, the author does not consider this a definite test of the Elliot model. In any case, if one did, the limiting flux would be 1.1×10^{-4} gammas $cm^{-2}sec^{-1}$.

In 1969 the OGO-6 satellite carried out neutron monitoring measurements in the energy range 1 to 20 MeV from June 1969 to December 1969 (Lockwood et al. 1972). The detector was a high pressure He-proportional counter in a plastic scintillator moderator to thermalize the fast (MeV) neutrons. The

anticoincidence charged-particle shield consisted of 22 proportional counters. Typical sensitivities for solar neutron spectra with characteristic rigidities P_o = 60 MV and 125 MV are 0.38 cm^2 and 0.37 cm^2 respectively. By carefully selecting the lowest background data (primarily low latitude) and using only data in a 6-months' period when no solar proton events were evident, a quiet time limit of 1.8×10^{-3} neutrons $cm^{-2}sec^{-1}$ was obtained. This result is about an order of magnitude lower than previously available in the same energy range. In addition, several small flares occurred during the experiment's lifetime, but no positive evidence for enhanced neutron fluxes was seen. No limit estimates were given for flares because of large statistical uncertainties. Figure 1 summarizes the current results on the continuous flux limits for solar neutrons as summarized by Lockwood (Private Communication).

A recoil proton telescope was also flown on the OSO-6 satellite to search for solar neutrons. Details on the instrument are not currently available, but continuous flux limits have been presented (Leavitt et al. 1972) as $<4 \times 10^{-4} cm^{-2} sec^{-1}$ for solar neutrons with energies greater than 40 MeV. Observations made by this instrument during solar activity are inconclusive.

A very interesting and new approach has recently been described by Kirsch (1972) using mountain altitude cosmic ray neutron monitors. Monte Carlo calculations (Alsmiller et al. 1968) have been carried out which give the conversion efficiency of solar neutrons in the Earth's atmosphere for yielding

secondary neutrons as a function of atmospheric depth. For example, Kirsch has used these basic results and calculated the efficiency for detecting different assumed solar neutron spectra at the altitudes of existing neutron monitors. For example, at 550 gm/cm^2 atmospheric depth, corresponding to the Chacaltaya monitor, the secondary neutron flux is 32 percent of the primary neutron flux assuming the producing-proton spectrum at the Sun has a characteristic rigidity R_o = 125 MV. Of particular interest here is the study made of the Chacaltaya and Mina Aguilas monitor data during the 12 November 1960 event for which Lingenfelter and Ramaty (1967) have predicted significant neutron fluxes. They predicted a flux of 10-33 neutrons/cm^2 sec at the Earth as a result of solar neutron production in the slowing down phase after particle acceleration. Kirsch's analysis (1972) indicates that the observed solar neutron flux is smaller by a factor of 10^{-2} to 10^{-3}. Therefore, it is concluded that the assumption of isotropic proton emission from the solar flare region is not fulfilled. One of the basic difficulties with this technique is the fact that any solar neutron effect must override the diurnal variation of cosmic rays.

All of the more recent results discussed above are summarized in Table I and should be self-explanatory.

III. OSO-7 OBSERVATIONS

We will now discuss in more detail the recent observations of solar gamma ray lines during the solar activity of early

August 1972, recently reported as preliminary observations (Chupp et al. 1972).

The seventh Orbiting Solar Observatory (OSO-7) carries in one of its wheel compartments the University of New Hampshire gamma ray monitor designed to study solar and cosmic gamma radiation in the energy range 0.3 to 10 MeV. The instrument has been described in detail by Higbie et al. (1972). It consists of a 3" by 3" NaI(Tl) crystal surrounded by a cup-shaped anticoincidence shield of CsI(Na). The energy resolution of the instrument for line radiation is ~8 percent at 662 keV. The instrument is calibrated regularly each orbit at day/night and night/day transitions with a Co^{60} source. The calibration gives photopeaks at 1.17, 1.33 MeV, and the sum peak at 2.50 MeV. With this calibration system we can determine the energy of a well-defined peak to within 2 percent anywhere in the pulse height spectrum.

During the normal mode of operation the pulse height spectra are accumulated over ~90 wheel rotations (~3 minutes) in the solar and background quadrants (Figure 2) and pulse height analysed with a 377-channel quadratic pulse height analyser (Burtis et al. 1972).

During the recent solar activity, beginning on 2 August 1972, we have observed gamma ray line and continuum emission from the Sun associated with the 2B flare on 4 August and 3B flare on 7 August 1972. A 2B Hα flare on 4 August began at 0621 UT reacing maximum at 0638 UT (Preliminary Report SESE-PRF-Boulder 092, 093). The OSO-7 gamma ray detector observed this flare until

0633 UT when the satellite was eclipsed by the Earth. Figure 3 shows a plot of the spectra which were taken just before the start of the optical phase of the flare (bottom) during the rise and just after the commencement of the satellite night. The total accumulation time of each pair of these spectra is ~9 minutes and the live time ranges from ~80 to 100 seconds. Figure 3(a) and (b) cover the spectral range ~430 to 620 keV and 2.1 to 2.4 MeV respectively. It is evident from the figure that during the rise of the reported flare there is significant enhancement in both the ~0.5 and 2.2 MeV spectral regions as well as in the continuum to above 2 MeV below the line features. Analysis of the data in other spectral regions shows possible evidence for the emission lines at 4.4 MeV and 6.1 MeV.

The gamma ray monitor has an auxiliary X-ray detector, NaI(Tl) crystal of diameter 1/4" and thickness 1 1/4", covering the energy range 7.5 to 120 keV in four steps. Figure 4 is a plot of the counting rate of X-ray Channel 4 (60 to 120 keV) versus time as recorded during the flare of 4 August. Also plotted in Figure 4 are the counting rates (above the continuum) of the line features 0.5 MeV and 2.2 MeV as a function of universal time.

In addition to the discrete line emission, we also observe significant enhancement of gamma ray radiation over the energy range 0.4 to 8 MeV. This is shown in Figure 5 where the average differential spectra (solar and background quadrants) measured during the rising phase of the flare are plotted. Also shown in the figure is the quiet time solar spectrum recorded just before

the onset of the flare. It can be seen from Figure 5 that the quiet time solar spectrum and the background spectrum are almost identical while the solar spectrum measured during the flare shows significant enhancement in the continuum below the line features.

The interpretation of the above observations implies production of discrete gamma ray lines by a variety of high energy processes taking place in the solar atmosphere. The probable sources of the gamma ray lines are positrons and neutrons produced in the nuclear reactions and high energy protons. Annihilation of positrons with electrons produces 0.51 MeV annihilation line while the 2.23 MeV results from the capture of neutrons by the hydrogen atoms. Inelastic scattering of fast protons on the less abundant C, N, O, and Ne nuclei produce a large number of weaker deexcitation gamma ray lines: 4.43 MeV (C^{12*}) and 6.13MeV (O^{16*}) is likely to be the most prominent. We believe that the line features we observe in the 2B Hα flare are the annihilation line (0.51 MeV), the neutron capture line (2.23 MeV) and the deexcitation lines of C^{12*} (4.43 MeV) and O^{16*} (6.13 MeV).

The enhanced continuum shows a large number of unresolved line features. At this stage we are not sure whether the continuum (particularly the high energy end) is due to electron bremsstrahlung or summation of unresolved line features.

It is appropriate to point out here that the gamma ray emission in solar flares could be of more complex character than

has been assumed in the past (Lingenfelter and Ramaty 1967). As discussed by Shima and Alsmiller (1970), the inelastic scattering of protons (50 MeV) on C produces a line at ~2 MeV in addition to the 4.43 MeV line, while the 15 MeV protons on O^{16} yield prominent lines at ~4.4 MeV and ~5.2 MeV in addition to the 6.13 MeV line. Thus the possibility that more than one source is contributing to the observed line features cannot be ruled out.

The 3B flare of 7 August provides additional evidence for the emission of 0.5 and 2.2 MeV in solar flares. The 3B flare began in Hα at ~1500 hours UT (Preliminary Report SESC-PRF-Boulder 092, 093) when the OSO-7 satellite was behind the Earth. Approximately 40 minutes after the onset of the flare, the satellite emerged into sunlight and enhanced counting rates in the spectral regions around ~0.5 and 2.2 MeV were observed. Figure 6 is a plot of the counting rate spectra measured during the onset (nighttime) and declining phase (daytime) of the flare. The first solar spectrum measured after the commencement of the satellite day shows enhancement in the regions corresponding to the photon energies of 0.5 and 2.2 MeV. Although the enhancement is not as large as observed for the 4 August event, but since it appears only in the solar spectrum, it can be argued that it could not arise due to local satellite or atmospheric effects.

The enhancement in the background quadrant ~0.5 MeV region in the upper spectrum of Figure 6(a) is perhaps genuine. During this time the detector was looking at the Earth with good aspect and picked up 0.51 MeV annihilation radiation from the atmosphere.

Table 2 lists tentative fluxes at the Earth for the gamma ray lines observed during the flares of 4 and 7 August.

In conclusion, it is clear that the gamma ray production expected during the solar flares has now been observed, and in addition, the presence of simultaneous neutron production is indirectly confirmed through the observation of the 2.2 MeV gamma ray line. When taken with correlated observations of the other radiations emitted during the flare, we believe these gamma ray observations have opened a new dimension into the study of the overall solar flare and solar cosmic ray phenomena.

IV. THEORETICAL IMPLICATIONS

In view of the lack of any believable positive results, prior to August 1972, concerning solar neutrons or solar gamma ray fluxes, it had become increasingly evident that some revision was necessary in the simple models describing neutron and gamma ray production in the solar atmosphere. Essentially all the model calculations assumed an isotropic release of accelerated particles into the solar atmosphere. This model gives the largest yield of gamma rays and neutrons, but Lingenfelter and Ramaty (1967) have also considered the production during acceleration in a low density medium where the yield is relatively low. From the failure to detect either gamma rays or neutrons during any solar activity since 1960, it is at least necessary to conclude that the isotropic-release model for solar protons is untenable. This conclusion is supported most strongly by the work of Kirsch (1972).

Table 2

Associated Flare and the time of Observations	Tentative Designations and Preliminary Solar Flux at 1 AU Photons $cm^{-2}sec^{-1}$			
	0.5 MeV	2.2 MeV	4.4 MeV	6.1 MeV
2B (Hα) 4 Aug 1972 0626 - 0632 UT (Before Hα Max)	$(7\pm1.5) \times 10^{-2}$	$(2.2\pm0.2) \times 10^{-1}$	$(3\pm1) \times 10^{-2}$	$(3\pm1) \times 10^{-2}$
3B (Hα) 7 Aug 1972 1538 - 1547 UT (After Hα Max)	$(3.7\pm0.9) \times 10^{-2}$	$(2.6\pm1) \times 10^{-2}$	$<2 \times 10^{-2}$	$<2 \times 10^{-2}$

Until the August 1972 solar flares, there has not been a good opportunity to test the preflare acceleration ideas of Elliot (1969). With the observation of strong emission of gamma ray lines during the rise of the 4 August event, it is likely the particle acceleration also occurred during this time. Since the data now exists from the OSO-7 experiment, a careful search will be made to see if there is any evidence for preflare acceleration of protons during the whole activity period from 2 August to 12 August; therefore, a definitive answer on the Elliot model should be soon forthcoming.

Several interesting inferences are now available from the OSO-7 observations. From the time profile of the 0.5 and 2.2 MeV lines shown in Figure 4, we can put an experimental upper limit on the acceleration time for solar protons during the flare of 4 August. Since the time resolution of the instrument for the gamma lines is 3 minutes, one can see that the 0.5 MeV radiation rises to its maximum in no longer than about 10 minutes and it could be shorter. Unfortunately, the statistics are not good enough on the 4.4 and 6.1 MeV lines to plot a time-profile curve. Such lines should show a time profile that is exactly that of the protons, since these are prompt reemissions. Further analysis of this data may improve this.

From elementary considerations we may also estimate the flux of protons at the Sun required to produce the observed gamma ray intensity assuming protons are released toward the photosphere. This is most easily done using the measured intensity of the 4.4 MeV and 6.1 MeV gamma ray lines, since they are predominantly

produced by protons in the energy range $E_p \sim 10 \rightarrow 50$ MeV where the excitation cross-section is significant. The basic process giving rise to the gamma rays is inelastic scattering; for example, the protons on C^{12} populating the first excited state at 4.4 MeV followed by prompt deexcitation of the excited nucleus and giving a characteristic emission line at 4.4 MeV. This process is denoted as C^{12} (P, P^1, γ) and source strength, S, at the Sun may be expressed as

$$S\left(\frac{\text{gammas}}{\text{sec}}\right) = N(n_i t)\sigma,$$

where N is the number of protons/second incident on the solar atmosphere, $(n_i t)$ is the thickness of the target measured in the number of carbon nuclei/cm^2, and σ is the average inelastic excitation cross-section over the energy range 10 to 50 MeV. The target area density $(n_i t)$ may be expressed as

$$(n_i t) = f_c R/m_p,$$

where f_c is the fractional solar atmospheric atomic abundance of carbon relative to hydrogen $\sim 5.3 \times 10^{-4}$, R is proton range in hydrogen for 50 MeV protons and m_p is the proton mass (gms).

The source strength obtained from the observed flux is $S(4.4) \sim 10^{26}$ photons/sec emitted isotropically from the Sun. Using this result, $R(50 \text{ MeV}) = 1$ gm/cm^2, and $\sigma(4.4) \sim 1.2 \times 10^{-25}$cm^2, the proton current in the solar atmosphere is $N \doteq 2 \times 10^{30}$protons/sec. This means that over approximately the 1000 seconds the

main burst lasted, about 2×10^{33} protons of energy 10 to 50 MeV were impinging into the denser solar atmosphere.

Deuteron production in the solar atmosphere from neutron capture may also be estimated from the observed flux of 2.2 MeV photons which also gives directly the production rate of such photons on the Sun. Since this production rate is the capture rate of neutrons, it is also the production rate of dueterons by this source, and for the observed flux of 2×10^{-1} photons $cm^2 sec^{-1}$, we find $\sim 6 \times 10^{26}$ deuterons produced/second by neutron capture. This is undoubtedly a very small source of deuterons since many more must be produced in the He breakup reactions which produced the neutrons in the first place (Lingenfelter and Ramaty 1967).

Further analysis of the OSO-7 solar events will be required before we can be sure of final conclusions and interpretations. One of the principal goals of further analysis is to determine if nuclear line emission is only observable in very large events or if they are more frequent and their frequency correlated with the frequency of the larger (X-class) X-ray bursts. In addition, the gamma ray spectra will have to be studied very carefully for evidence for Doppler line shift or broadening. Finally, by correlating with solar proton observations, we hope to learn more about the spectrum of the protons accelerated at the Sun.

V. CONCLUSION

Since the prediction of solar flares is still a somewhat "Shaky Art", it is clearly advisable to keep gamma ray monitoring

experiments continuously in space as the solar cycle advances. Without question it is also possible to greatly improve on the present instrument with the capabilities of existing spacecraft. The most desirable detector improvements that should be made are background reduction, increased sensitivity and improved energy and time resolution, all of which are easily attainable.

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FIGURE CAPTIONS

Figure 1 Summary of the upper limits to the differential solar neutron flux at Earth. For E>50 MeV the upper and lower limits indicated with a band include many results not shown in the figure. The curve marked Lingenfelter and Flamm (1965) is the calculated time-average solar neutron flux at Earth for the last solar cycle.

Figure 2 A schematic drawing of the gamma ray spectrometer is shown with the OSO wheel in the position for viewing the Sun. The solar and background quadrant identifications are also shown. The small inset at the right shows satellite aspect at sunrise and at noon and at sunset.

Figure 3(a) The gamma ray pulse height spectrum is shown for the energy region 460 keV to 620 keV on 4 August 1972. The lower spectrum was taken in the daytime before the start of the 2B Hα flare and the central spectrum was taken during the rise of the optical flare. The spectrum at the top was taken just as the satellite was occultated by the Earth. The accumulation time intervals are shown for each spectrum.

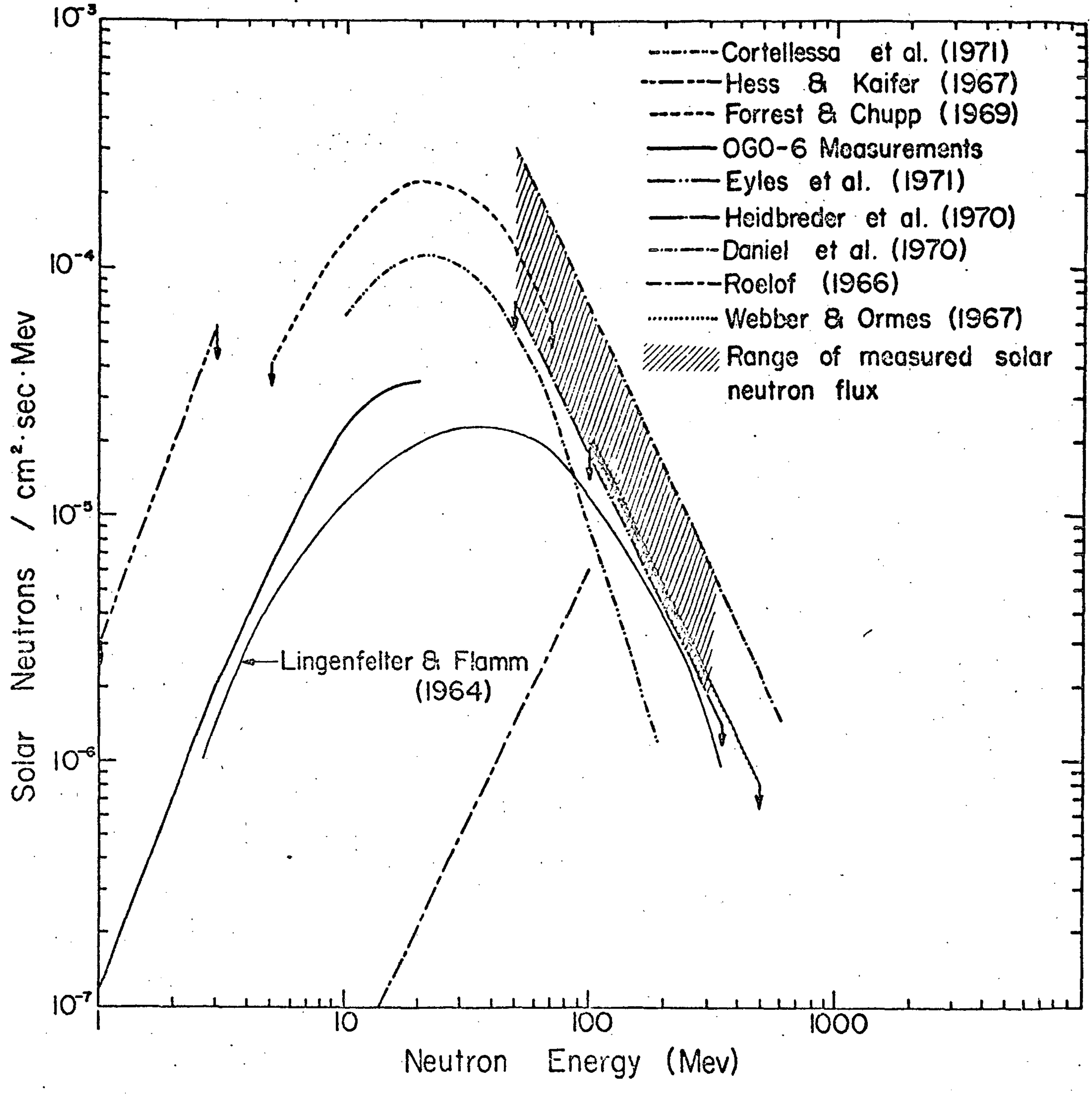
Figure 3(b) The gamma ray pulse height spectrum is shown for the energy region 2.1 MeV to 2.4 MeV on 4 August 1972. The lower spectrum was taken in the daytime before the start of the 2B Hα flare and the central spectrum was taken during the rise of the optical flare. The spectrum at the top was taken just as the satellite was occultated by the Earth. The accumulation time intervals are shown for each spectrum.

Figure 4 The time profile for the counting rate in one X-ray channel (60 to 120 keV) is shown covering the period of satellite day from about 20 minutes before the optical onset until the satellite went into eclipse. Also shown are the time prifoles for the counting rates in the five channels corresponding to gamma ray lines at 0.5 MeV and 2.2 MeV. (Preliminary data.)

Figure 5 Differential pulse height spectra (solar and background quadrants) observed during the 2B flare on 4 August 1972. The spectra were measured after the onset of the flare and cover the period 0626 to 0632 UT. Also shown is a typical solar quadrant spectrum taken just before the onset of the flare.

Figure 6(a) The gamma ray pulse height spectrum is shown for the energy region 440 keV to 610 keV on 7 August 1972. The lower spectrum was taken at nighttime just before the satellite sunrise, but while the 3B optical flare was in progress. The second spectrum from the bottom was taken just after the sunrise calibration and during the declining phase of the optical flare. The top two spectra were taken at later times in the same orbit during the satellite daytime. The accumulation time intervals are shown for each spectrum.

Figure 6(b) The gamma ray pulse height spectrum is shown for the energy region 2.1 MeV to 2.4 MeV on 7 August 1972. The lower spectrum was taken at nighttime just before the satellite sunrise, but while the 3B optical flare was in progress. The second spectrum from the bottom was taken just after the sunrise calibration and during the the declining phase of the optical flare. The top two spectra were taken at later times in the same orbit during the satellite daytime. The accumulation time intervals are shown for each spectrum.



Cortellessa et al. (1971)
Hess & Kaifer (1967)
Forrest & Chupp (1969)
OGO-6 Measurements
Eyles et al. (1971)
Heidbreder et al. (1970)
Daniel et al. (1970)
Roelof (1966)
Webber & Ormes (1967)
Range of measured solar neutron flux
Lingenfelter & Flamm (1964)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
1
10
100
1000
Solar Neutrons / cm²·sec·Mev
Neutron Energy (Mev)

Fig. 1

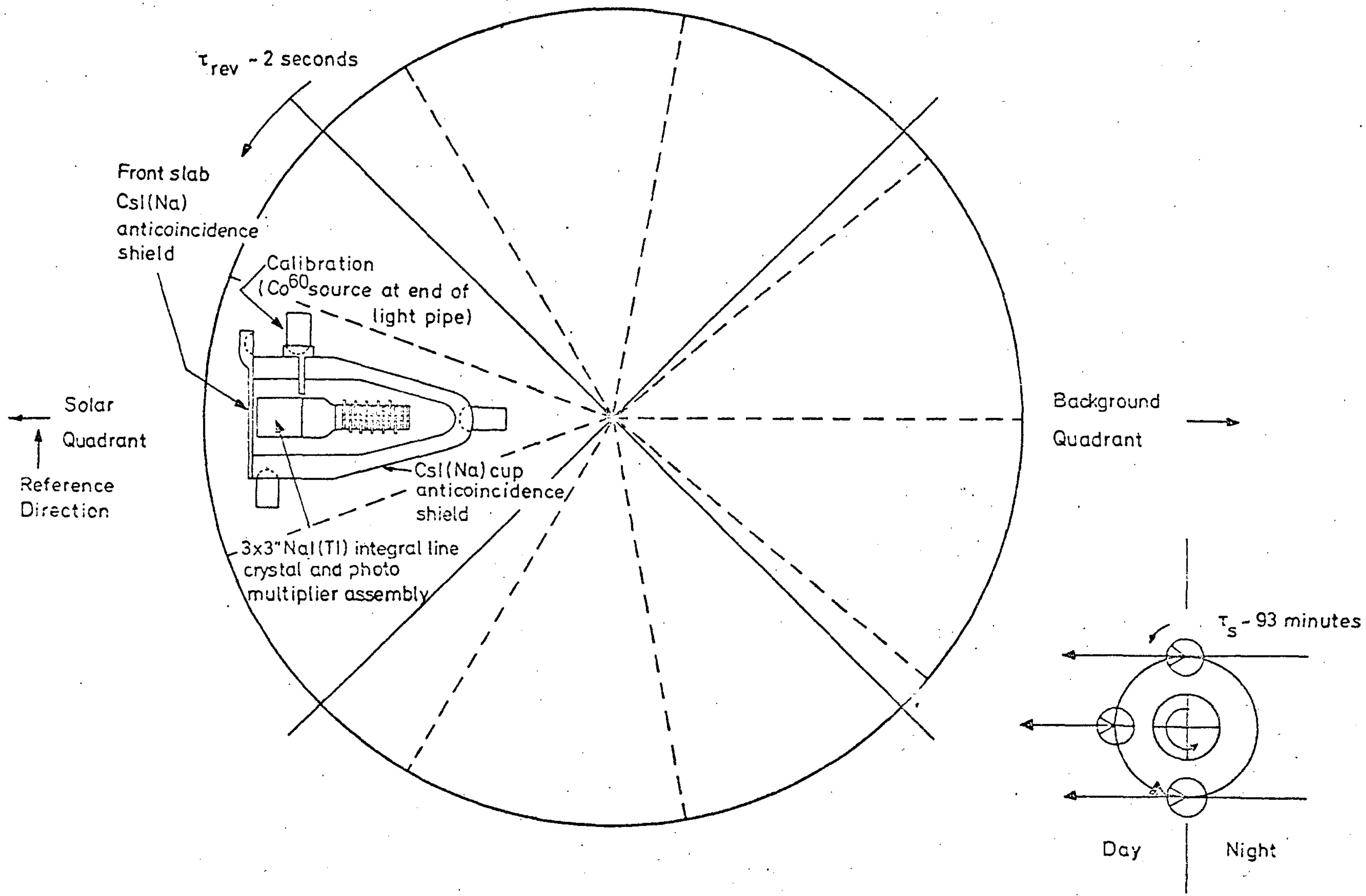

τ_{rev} ~ 2 seconds
Front slab
CsI(Na)
anticoincidence
shield
Calibration
(Co^{60}source at end of
light pipe)
Solar
Quadrant
Reference
Direction
Background
Quadrant
CsI(Na) cup
anticoincidence
shield
3x3" NaI(Tl) integral line
crystal and photo
multiplier assembly
τ_s - 93 minutes
Day
Night

Fig. 2

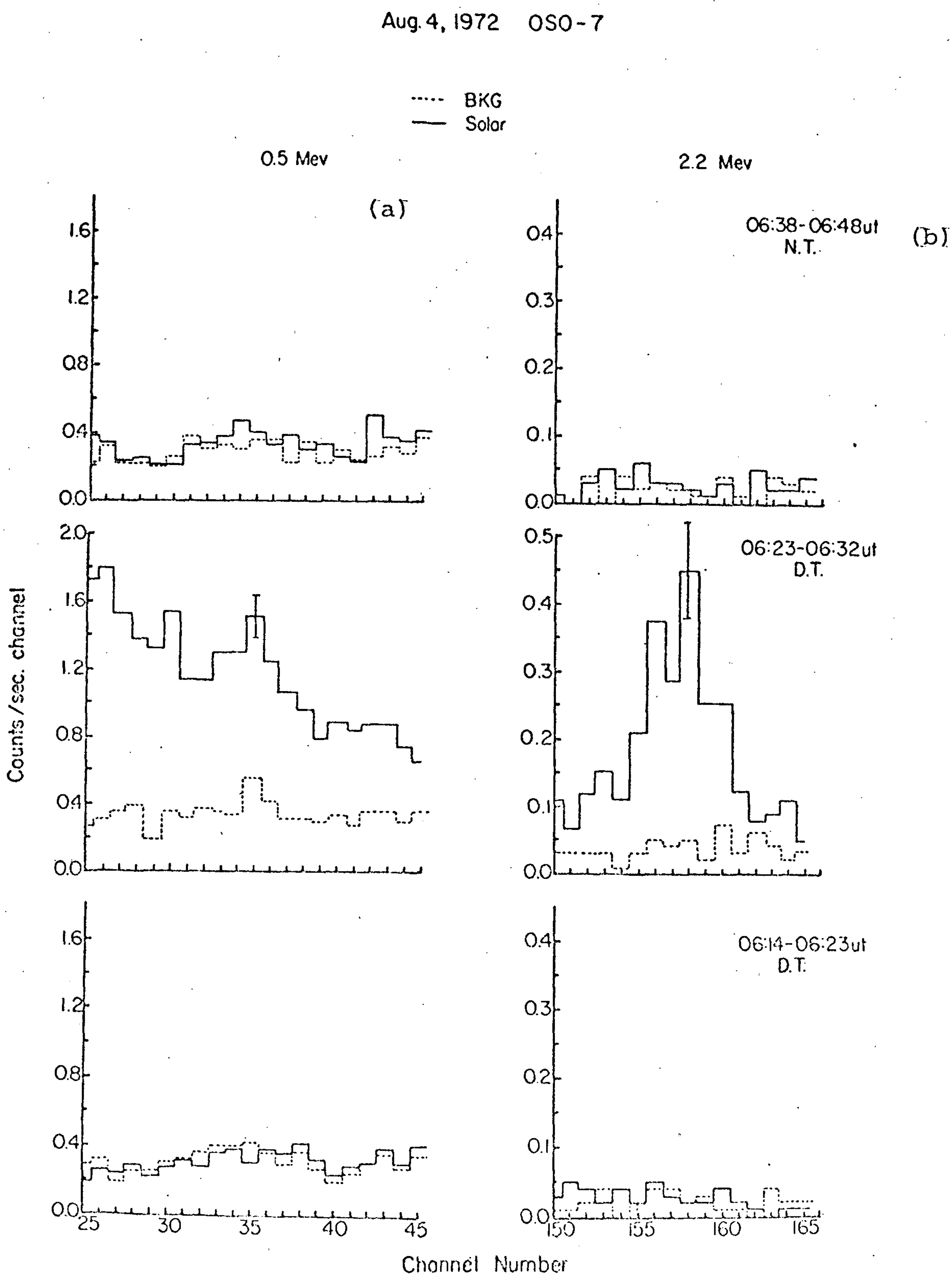
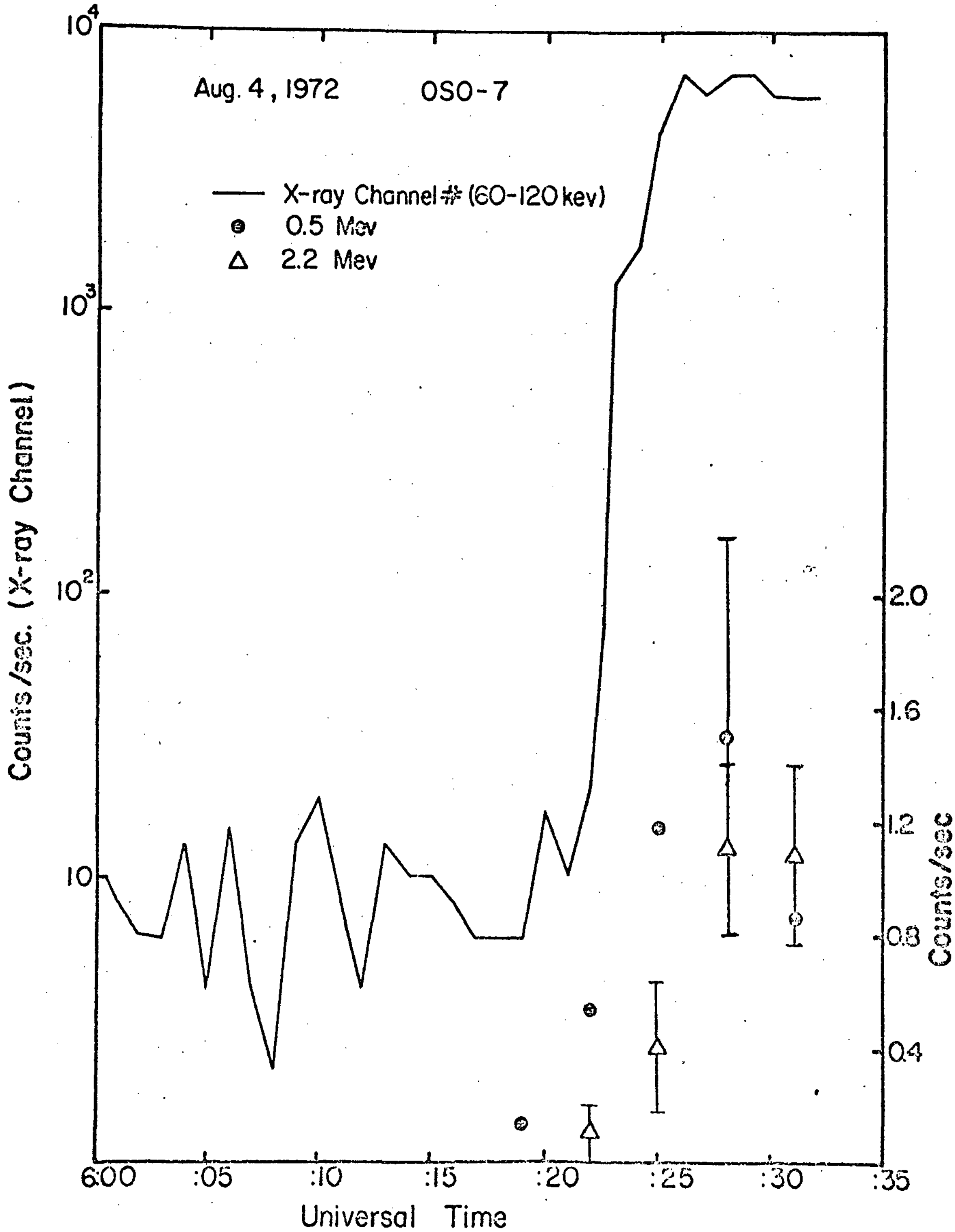
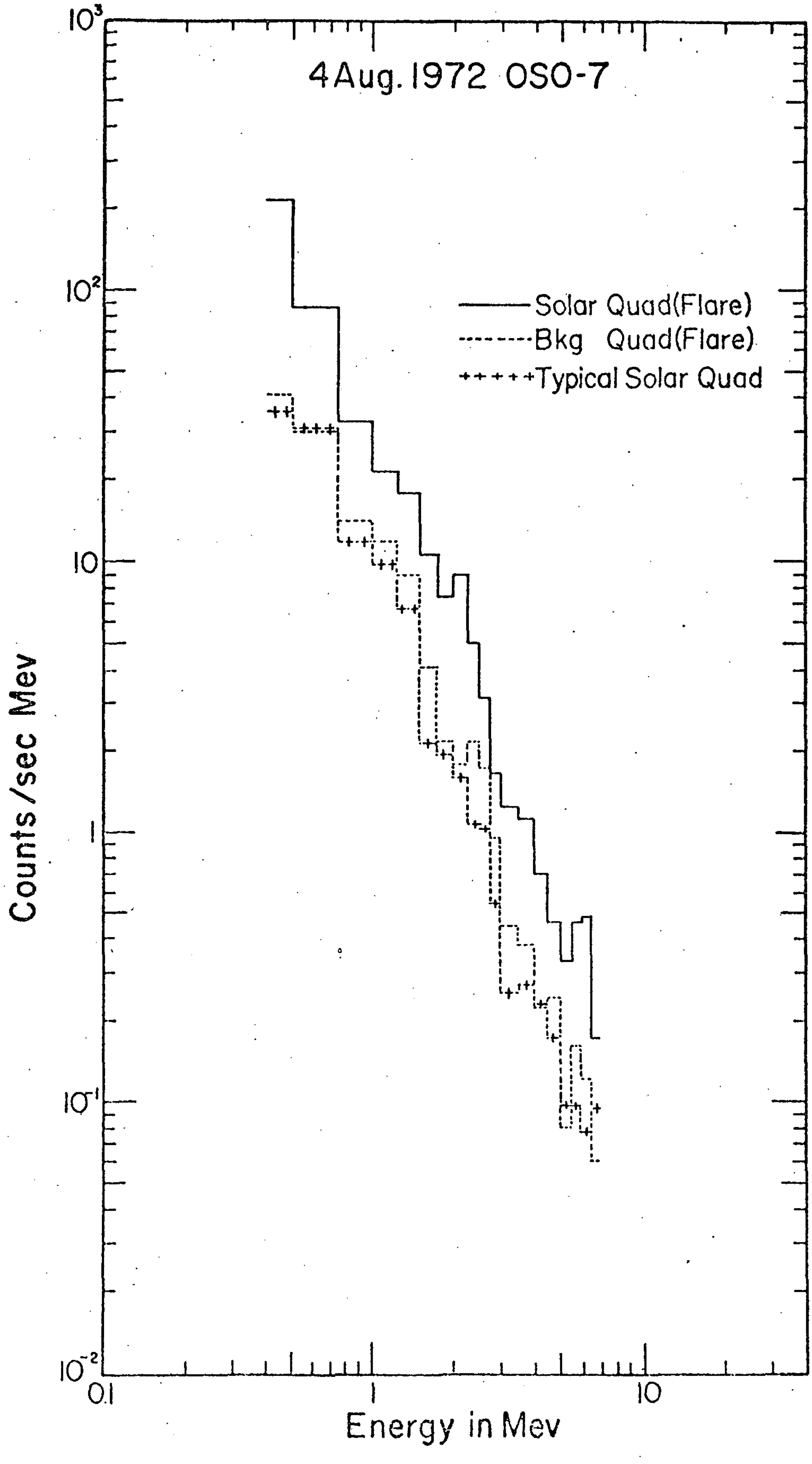

Aug. 4, 1972 OSO-7
BKG
Solar
0.5 Mev
2.2 Mev
(a)
(b)
06:38-06:48ut
N.T.
06:23-06:32ut
D.T.
06:14-06:23ut
D.T.
Counts/sec. channel
Channel Number

Fig. 3



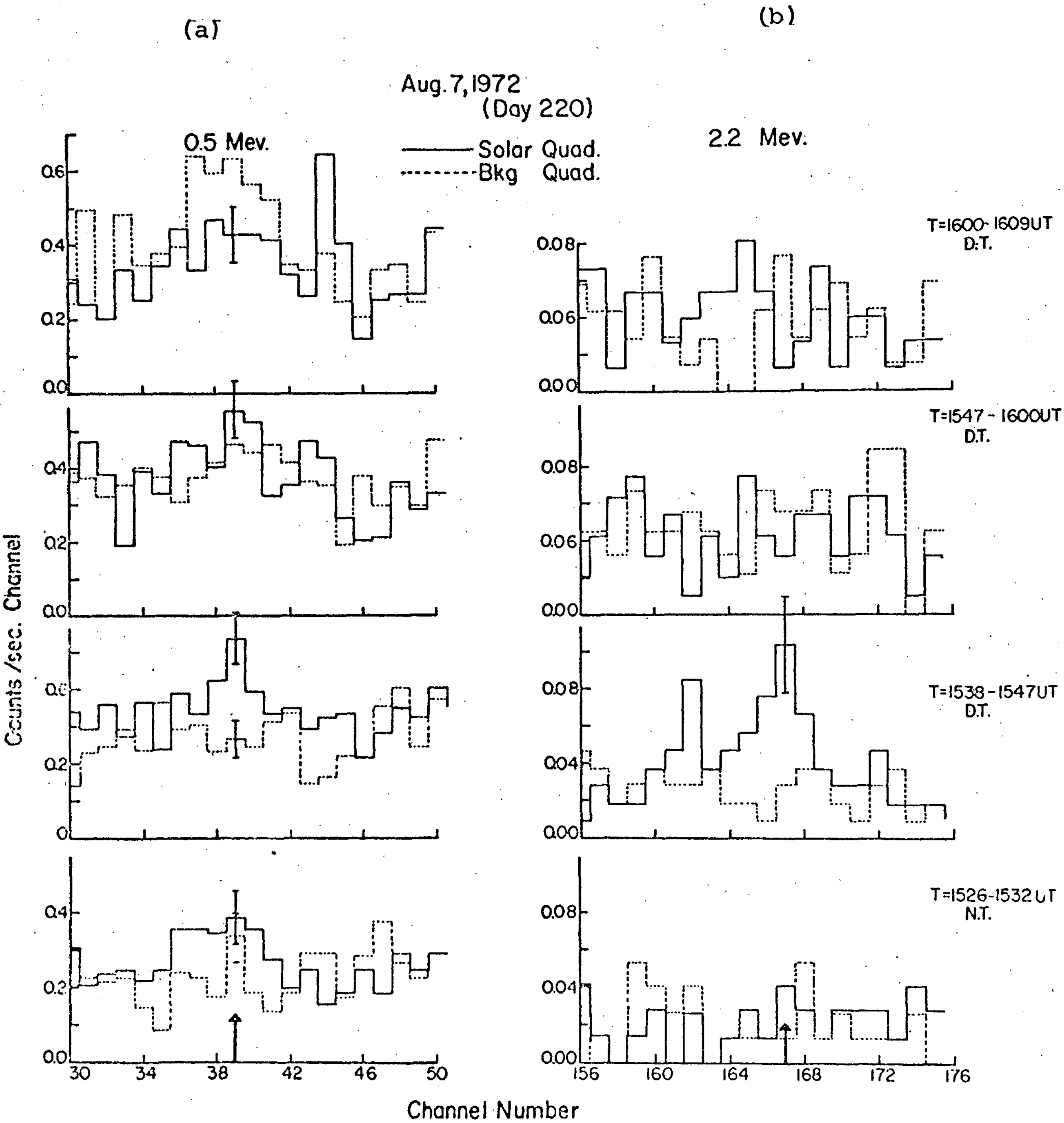
Aug. 4, 1972
OSO-7
X-ray Channel # (60-120 kev)
0.5 Mev
2.2 Mev
10^4
10^3
10^2
10
Counts/sec. (X-ray Channel)
2.0
1.6
1.2
0.8
0.4
Counts/sec
6:00
:05
:10
:15
:20
:25
:30
:35
Universal Time

Fig. 4



4 Aug. 1972 OSO-7
Solar Quad(Flare)
Bkg Quad(Flare)
Typical Solar Quad
Counts/sec Mev
Energy in Mev
10^3
10^2
10
1
10^{-1}
10^{-2}
0.1
1
10

Fig. 5



(a)
(b)
Aug. 7, 1972
(Day 220)
0.5 Mev.
2.2 Mev.
Solar Quad.
Bkg Quad.
T=1600-1609UT
D.T.
T=1547-1600UT
D.T.
T=1538-1547UT
D.T.
T=1526-1532 UT
N.T.
Counts /sec. Channel
Channel Number

Fig. 6